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Modelling the Impact of Array Wiring on Electrical Output of Vertical Bifacial Agrivoltaic Installations

W. Ross Rucker[1][https://orcid.org/0000-0001-5297-6994],
and Dunbar P. Birnie, III[1][https://orcid.org/0000-0001-6044-2300]

[1] Rutgers University, New Jersey, USA

Abstract. We present a model and study investigating the potential power output of vertical bifacial solar panels on New Jersey farms. The simulation calculates instantaneous brightness and shading based on the position of the sun and adjacent rows of panels, and uses that to calculate current and voltage values. We explore different strategies to improve the power output further. Double-high modules, which use two panels stacked together, offer significant gains per acre with only a modest increase of inter-row shading. When bypass diodes and improved inverter wiring are also used, much of the losses due to shading are avoided, and the total power output per acre is nearly doubled. In a double high configuration it is advantageous to have the top and bottom modules on seperate inverter strings.

Keywords: Agrivoltaics, Vertical Bifacial Panels, Modelling

1. Background

1.1 Vertical Bifacial Panels

The Rutgers Agrivoltaics Program is a group of farmers, engineers, economists, and sociologists assessing the viability of agrivoltaic installations and applicability in New Jersey. As part of our investigations, we have become interested in the vertical bifacial (VBF) design pioneered by Next2Sun [1], [2]. Bifacial solar panels utilize novel silicon wafer back-contacting to absorb photons with both the front and the back of the panel, allowing for greater efficiency [3]–[5]. Due to their upright orientation, VBF panels do not need to be raised up on elaborate steel canopies and can be installed in a way that makes it very easy for tall farming machinery to pass between the rows without worrying about clearance height. This creates fewer disruptions to normal farming operations and crop yield [6]. Unlike traditional fixed tilt or tracker solar panels, VBF panels are installed closer to the ground in a way similar to fence posts, potentially keeping installation costs low. Additionally, installing them lower to the ground makes them much easier and cheaper to clean, avoiding losses due to soiling [4], [7]–[10]. Several studies have covered basic sunlight models that estimate the energy output as a function of pitch and height [4]–[6], [8], but certain circuit complexities of the inverter connections have not been fully explored and are addressed in the present work.

1.2 Strategies to Improve Power Output

Generally speaking, VBF panels do not achieve the same efficiency as their fixed tilt or tracker counterparts. Because they are situated vertically, their power generation peaks in the morning and afternoon instead of midday when sunlight is the strongest. While late afternoon production can have certain benefits, most net-metered solar producers are only paid on a pure output basis regardless of hourly grid demands and would not see any benefit from targeting a time of day.

We focused on three strategies to improve the modules' overall efficiency and simulated the results of employing those tactics. First, we examined how bypass diodes (frequently included in modern module designs) improved the output. Second, we examined how double-high module racking improves the output and its impact on overall shading across panels. Last, we calculated the improvement in output from double-high VBF installations when the top and bottom halves are wired into separate inverters.

1.3 Modelling Language and Dependencies

Our modelling was done in Python 3.7 [11], and used NREL's PVlib library to calculate the movement of the sun throughout the year [12]. These functions provide the angle and position of the sun at any time of day for a given latitude and longitude position. We calculate the zenith and elevation of the sun at five-minute intervals. For our calculations, we used the coordinates of New Brunswick, New Jersey (40.5, -74.4), the location of Rutgers University's main campus, and also the location of a planned VBF solar research site. We also rely on the National Solar Radiation Database (NSRDB) data for empirical solar radiation data that includes typical weather variations [13]. We use the hourly Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) values for the year of 2019, again for New Brunswick, New Jersey. We used linear interpolation between the hourly interval data to provide realistic DNI and DHI at five-minute granularity.

2. Methodology

2.1 Illumination Modelling

The dimensions of the panels, how high off the ground the panel sits, and the row pitch are all taken into consideration in order to determine how much illumination each modules receives, how much shade they cast, where their shadow lands relative to adjacent rows, and ultimately how much power they can produce for different wiring configurations.

In our simulation, we subdivided the panel height into 120 discrete positions from top to bottom and evaluated the brightness at each location at each time interval throughout each day. During the early morning and late afternoon, there are circumstances where one row of panels casts a shadow on part of the next row, as illustrated in Figure 1. At each five-minute time interval, we use a DNI value proportional to the source data as a function of the sun's angle at that moment. If the position we are evaluating is determined to be in the shadow of another panel, the DNI contribution is zero for the shaded areas. For the DHI, we calculate the impact of shade or blockages caused by other panels from all possible angles and then assign a value proportional to the source data for that time and subject to the fraction of full hemispherical sky-view from which scattered light will be received. Inherent to the VBF design is the bifacial silicon wafers, though there is also a penalty applied when either type of irradiance interacts with the back of the panel, as it is noted in literature that the backside of bifacial panels is less efficient than the front [14], [15].

The height of the module is an important factor to consider where planning an array of VBF panels. Double-high modules stack one panel on top of another, which obviously increases the amount of active solar cells which can be installed per acre of land, but the taller a module is, the more shade it casts on adjacent rows. In the early morning hours near dawn and late afternoon hours near dusk, when sunlight is coming from angles close to the horizon, the top rows of cells in a panel will receive very different amounts of sunlight from the bottom cells. Figure 1 shows an illustration of how light may fall on the panels or be blocked throughout the day. The difference in sun angle or shadow can result in an enormous difference between the illumination that reaches the top row of cells and the bottom row of cells.

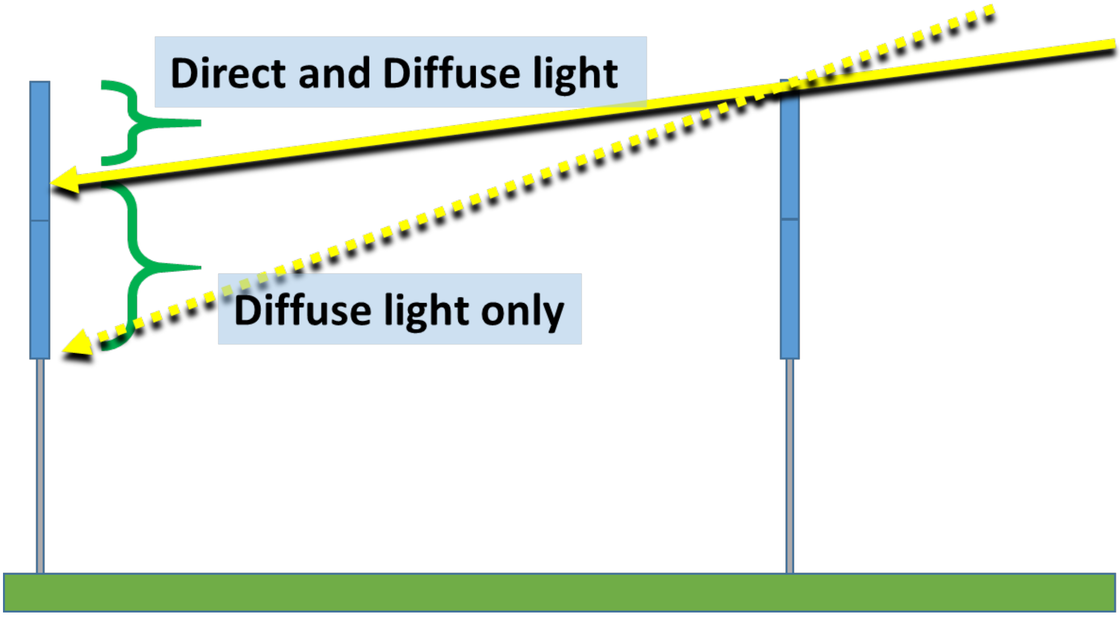

Figure 1. An illustration of cross-row shading on VBF panels. The sun angle and panel dimensions makes it so some regions of the panels will only receive diffuse light.

The spacing between rows, or pitch, of VBF panels is a critical variable to consider. There are several competing interests at play. On one hand, a solar developer will want to maximize their return by installing the optimal number of solar cells present in a field in order to get the highest amount of electrical output. However, in an agrivoltaic installation, we must always consider the farmer working the field. Rows must be spaced far enough apart for sunlight to reach the crops and for large farm machinery and other vehicles to pass through the rows without issue in order for proper tilling, harvesting, and other operations to continue unhindered. Farmers may want more space than just the width of their machines in order to make turning easier or minimize risk of colliding with the panels. As it is beneficial for both the farm and the panels to be some distance apart, we do not consider any pitch less than 20 feet in this model.

2.2 Module Performance Modelling

When inter-row shading happens, it is necessary to model the module performance taking into account each individual silicon wafer's response to its local illumination level. Equation 1 shows the diode equation that governs the I-V response for any given wafer subject to incoming light level differences, I_{ph}. I_o is the dark saturation current, V is the voltage, V_t is the thermal voltage, R_s is the series resistance, and R_{sh} is the shunt resistance. Finally, a diode ideality coefficient, a, is required. The main restriction within a module is that all wafers must be operating at the same current value, though with different illumination they will each deliver slightly different voltages, which are then summed to calculate the module output power for a given condition.

$$I = I_{ph} - I_o \left[e^{\left((V+IR_s) / aV_t \right)} - 1 \right] - \frac{V+IR_s}{R_{sh}} \quad (1)$$

Figure 2 shows the I-V curves and our fittings for bifacial solar panels with differing levels of illumination. Notably the least illuminated wafers will typically govern the maximum current allowed.

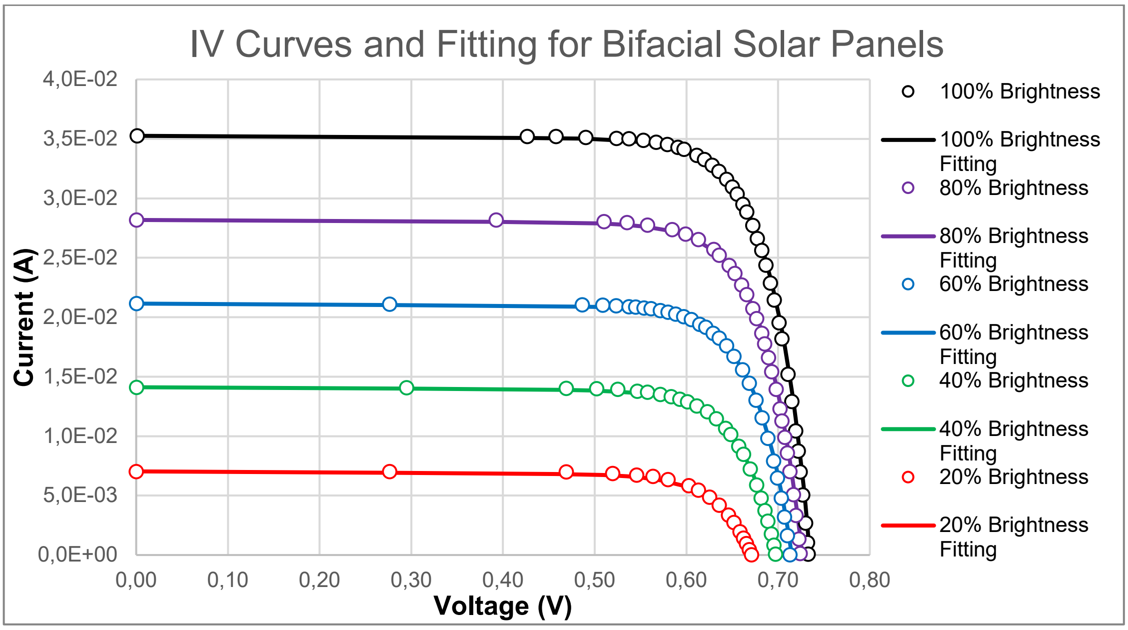

Figure 2. A chart showing IV curves and fittings for bifacial panels at different levels of illumination. Adapted from Luxor Solar [16].

Modules with bypass diodes are able to reduce the low-light weak link by allowing current to bypass a badly underperforming zone of the module. If a region of the panel governed by a bypass diode is underperforming, the diode can activate, effectively turning off that string of cells and giving up its output in order to allow the rest of the panel to operate at a higher current to produce more power. We used a 3 diode per panel configuration that has been adopted by many module manufacturers at this point. When considering a double-high module that is wired in series, there are a total of 6 diodes. Figure 3 shows an illustration of how electricity would flow through a panel with a shaded lower region causing the bypass diode to be activated. Figure 4 shows a graph of how bypass diodes improve the output of a double-high module during a sunny day with consistent sunlight and no unusual weather events.

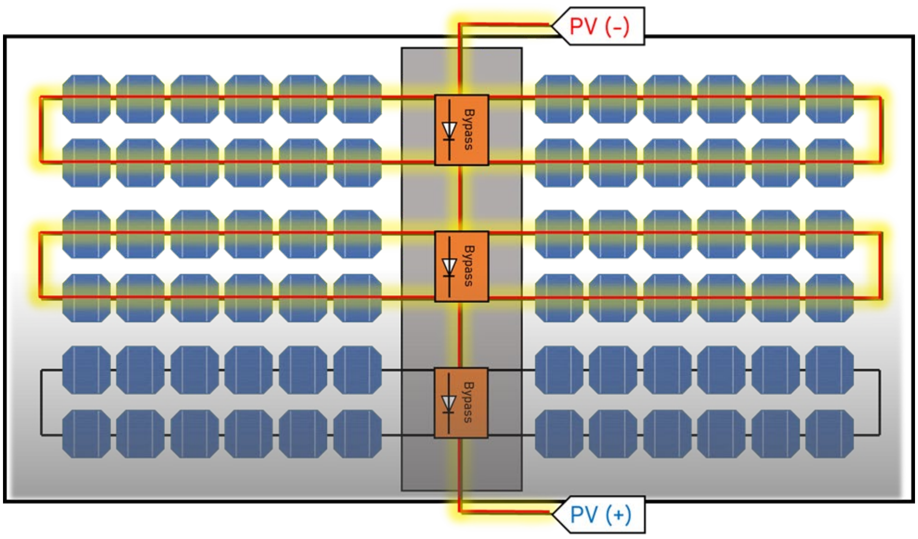

Figure 3. A graphical representation a solar panel governed by three bypass diodes situated vertically in the center of the panel. The glowing red line follows the path that leads to the greatest output power, based on the voltage of cells in series and the current from illumination. As the bottom area of the panel is under shade, those strings of cells are being bypassed to acheive a higher power output from the brighter top section.

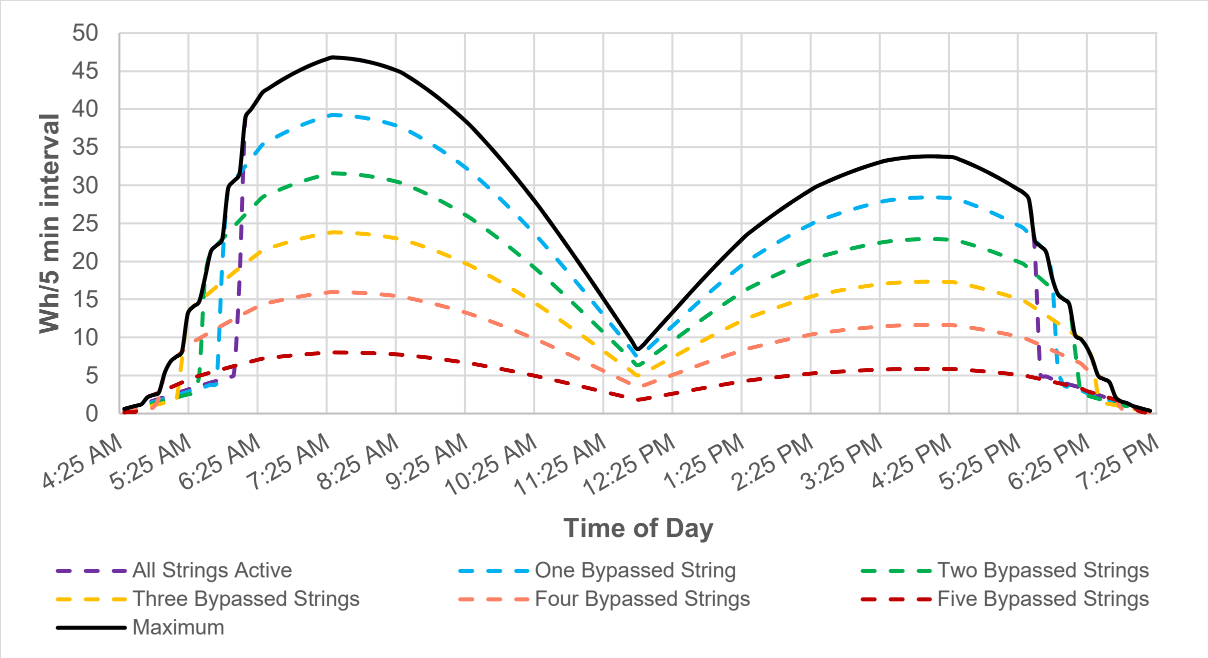

Figure 4. A chart plotting the energy output of a double-high VBF panel using six bypass diodes throughout the day of June 4th, 2019. Each panel is 2 meters tall and spaced 20 feet apart from the next row of panels. Some cells are bypassed during early morning and late evening, resulting in a step-up/step-down effect at the edges. The solid black line follows the maximum power throughout the day.

3. Results

The inclusion of bypass diodes offers an increase of nearly 4% to power output when panels are placed close together, with diminishing gains when the panels are spaced further apart. The advantage of bypass diodes is mitigating the effects on shading causing a non-uniform illumination gradient across the panel. Since panels which are far apart will have less shading anyway, this result is expected.

Switching from single-high to double-high offers a significant, though not quite double, increase in annual energy output per acre, though on a per-square-meter basis there is a loss as the extra shade from the taller panels reaches over to neighboring rows.

The gains from using a second, decoupled inverter are important, too; these benefits are diminished when the rows are installed farther apart; the improvement is less than 1% when the pitch is 100 feet compared to the roughly 6% gained at the 20-foot row spacing. Like the bypass diodes before, this is due to the shade from neighboring panels being relatively negligible at a high pitch, which is the main issue that decoupling the inverters aims to solve. A further array design adjustment would be to add DC-DC power optimizers to the modules, which would achieve a similar result as decoupling the top and bottom modules, but with the added installation cost.

Projected electrical output values for all calculated cases along with the percent difference when compared to values for a standard single-high module of the same pitch are shown in Tables 1 and 2 below. The panels are assumed to be 2 meters tall, installed in landscape alignment, and where the bottom edge is elevated 2 meters off the ground.

Table 1. Energy output reported in kWh/year/m^2

Pitch	Single-High	Single-High w/ Bypass Diodes	Double-High w/ Bypass Diodes	Decoupled Double-High w/ Bypass Diodes
20 ft (6.1 m)	235.47	244.61 (3.88% gain)	231.85 (1.54% loss)	238.89 (1.45% gain)
40 ft (12.2 m)	273.45	276.61 (1.15% gain)	261.38 (4.42% loss)	263.61 (3.60% loss)
60 ft (18.3 m)	284.16	285.92 (0.62% gain)	269.97 (4.99% loss)	271.07 (4.61% loss)
80 ft (24.4 m)	289.02	290.21 (0.41% gain)	273.94 (5.22% loss)	274.61 (4.99% loss)
100 ft (30.5 m)	291.77	292.67 (0.31% gain)	276.21 (5.33% loss)	276.67 (5.18% loss)

Table 2. Energy output reported in kWh/year/acre

Pitch	Single-High	Single-High w/ Bypass Diodes	Double-High w/ Bypass Diodes	Decoupled Double-High w/ Bypass Diodes
20 ft (6.1 m)	73265.27	76108.11 (3.88% gain)	144278.9 (96.93% gain)	148659.4 (102.91% gain)
40 ft (12.2 m)	42541.48	43031.63 (1.15% gain)	81325.11 (91.17% gain)	82019.58 (92.80% gain)
60 ft (18.3 m)	29471.87	29654.25 (0.62% gain)	55999.60 (90.01% gain)	56227.52 (90.78% gain)
80 ft (24.4 m)	22481.73	22574.29 (0.41% gain)	46617.75 (89.57% gain)	42721.42 (90.03% gain)
100 ft (30.5 m)	18156.61	18212.19 (0.31% gain)	34376.03 (89.33% gain)	34433.33 (89.65% gain)

4. Conclusions

Our data show that agrivoltaic installations using VBF panels can produce competitive amounts of electricity per acre when spaced out and designed properly. Rows of double-high panels placed 20 feet apart with decoupled inverters can produce more than 148 MWh/year/acre and still leaves plenty of space for convenient farming operations.

Where cost allows, the double-high design has a clear advantage, producing much more energy per acre. When feasible, maintaining a pitch as close to 20 feet as possible should be the aim. When that is the case, wiring the cells with separate inverters for the top and bottom modules will improve the overall efficiency energy capture by the system. If the rows must be spaced further apart, the benefit of separate inverter wiring should be re-assessed, because it may not be cost-effective to do so. While using separate inverters will always be beneficial for the absolute electrical generation, that benefit is very small for wide pitch.

Data availability statement

Data used in the present modeling were accessed through NREL's National Solar Radiation Database and are publicly accessible at: https://nsrdb.nrel.gov/

Author contributions

Ross Rucker: Software, Methodology, Data Curation, Writing - Original Draft, Writing- Reviewing and Editing, Visualization. Dunbar Birnie: Conceptualization, Project Administration, Funding Acquisition, Methodology, Validation, Writing - Original Draft, Writing- Reviewing and Editing.

Competing interests

The authors declare no competing interests.

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